Studies of Mechanical and Tribological Phenomena in Ultrananocrystalline Diamond Thin Films

N. Moldovan (XFD-APS), D.M Gruen, J.A. Carlisle, O. Auciello, D. Wolf, S.R. Phillpot, D.C. Mancini (XFD-APS), Erdemir (ANL-ET), E. Stach (LBNL), V.P. Dravid (Northwestern), H. Espinosa (Northwestern)

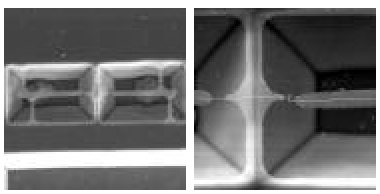
SCIENTIFIC ACHIEVEMENT

Ultrananocrystalline diamond (UNCD) films under investigation at Argonne National Laboratory exhibit a phase-pure diamond microstructure with 2-5 nm equiaxed grains, atomic scale (~ 0.2-0.5 nm) grain boundaries and extremely smooth surfaces (RMS roughness ~30-40 nm) due to the unique growth process based on the insertion of C_2 dimers (the dominant growth species in the microwave CH_4/Ar or C_{60}/Ar plasma used for film growth) in the growing film lattice. TEM studies have shown that the grain boundaries of UNCD films are atomically abrupt and devoid of non-diamond secondary phases, although UV Raman spectroscopy shows the presence of a few percent of sp^2 bonding. A tight binding pseudopotential calculation based on the assumption of randomly oriented nanometer-sized diamond grains predicts that the boundary is 3.56 Å wide, consisting of two opposing half-atomic layers from the two adjoining grains. The grain boundaries are predominantly high-energy boundaries with Σ 29 or Σ 13 character. Consequently, it is predicted that the brittle fracture strength of UNCD films is equal to or greater than that of even single crystal diamond. Nanoindentation measurements (load vs. indenter displacement into the film) indicate that UNCD films have hardness as high as about 97 GPa and Young modulus of about 970 GPa, both values very close to those of single crystal diamond. Pin-on-disk tribometry measurements, using SiC pins rubbing against flat diamond films on a substrate, revealed that UNCD films exhibit a substantial lower wear rate (~ 0.018 x 10^{-6} mm^3/N-m) than that of microcrystalline diamond (MCD) films (~ 1x10^{-6} mm^3/N-m). In addition, measurements of coefficient of friction (COF) showed that the COF of as-deposited UNCD films is as low as 0.02 (similar to that of single crystal diamond), i.e., much lower than that of as-deposited MCD films (~ 0. 5). In addition to the studies described above, we recently performed the first investigation of mechanical strength of UNCD films using a unique integrated TEM / nanoindenter (in collaboration with E. Stach from Lawrence Berkeley Laboratory) that allows to study mechanical strength while simultaneously observing microstructural changes in the material. Further studies currently in progress will provide unique insights into microstructure-property relationships of UNCD.

SIGNIFICANCE

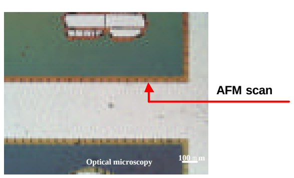
The unique mechanical and tribological properties of UNCD films described above make this material ideally suited for fabrication of microelectromechanical systems (MEMS), micromechanical assemblies (MMA) and macroscopic systems requiring materials with high hardness, extremely low coefficient of friction and wear rate. In this respect, we have successfully demonstrated the fabrication of various MEMS components based on UNCD such as micro-gears, pinwheels, cantilevers and strain-gauges with spatial resolution down to 100 nm, which demonstrates the feasibility of developing a whole new MEMS technology based on UNCD. In addition, we have demonstrated that the UNCD coatings can be applied on high aspect ratio Si structures with extremely good conformality. MEMS structures based on UNCD will provide the means for investigating mechanical and tribological properties at an scale not previously available to researchers.

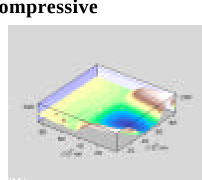
Measurement of stress in UNCD films

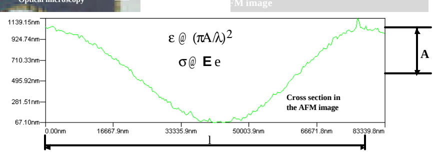


Micromechanical stress measuring gauges

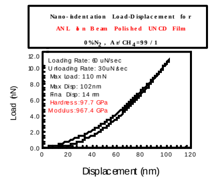
The "overhang method":
s @ 50-310 MPa, compressive

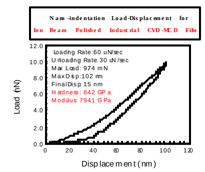




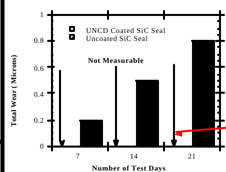


Mechanical and Tribological Properties of UNCD Films

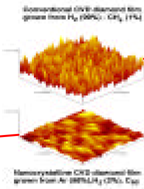




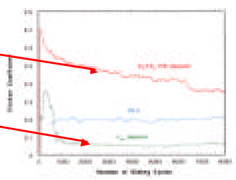
Nanoindentation reveals that UNCD films are as hard as single crystal diamond



Wear test of UNCD - coated mechanical pump seal shows practically no measurable wear as opposed to uncoated SiC industrial standard



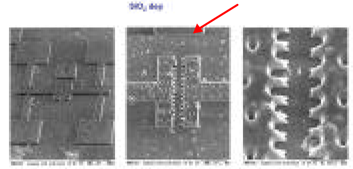
UNCD films are much smoother than MCD films, resulting in much lower friction coefficient and wear

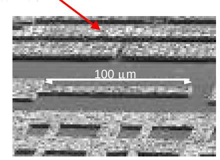


Coefficient of friction of UNCD films are much lower than for MCD and diamond - like films

Friction coefficient and wear test on UNCD and competing diamond and diamond-like films
Show the outstanding properties of UNCD films

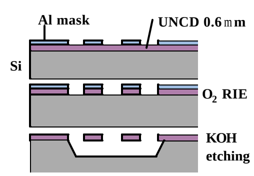
Microfabrication Process for 2-D MEMS Structures

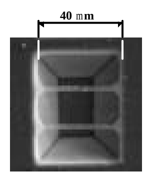


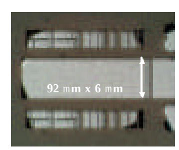


2-D high resolution (~ 100 nm) UNCD gauge

2-D UNCD cantilever suitable for fabrication of photonic and RF switches

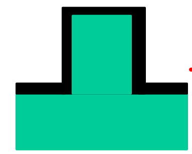




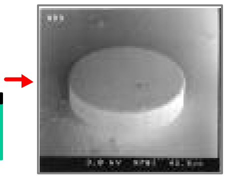


Free-standing structures for measuring mechanical properties of UNCD

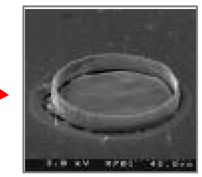
3-D MEMS Structures



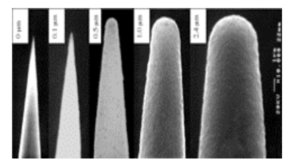
Conformal growth of UNCD on Si post



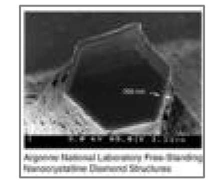
Ion bombardment of top surface of UNCD-coated Si post to etch UNCD layer



Selective chemical etching of exposed Si core to produced UNCD ring structure

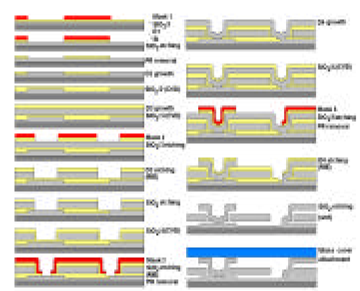


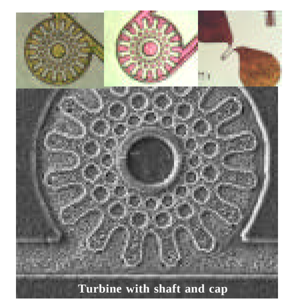
Conformal growth of UNCD on Si high aspect ratio microtip



Selective chemical etching of Si core to produce hollow UNCD 3-D structure

UNCD-Based Microturbine





CONCLUSIONS

A novel microwave plasma chemistry produces UNCD films with unique mechanical and tribological properties, such as hardness and friction coefficient similar to single crystal diamond and extremelly low wear. These properties make UNCD a very suitable material for the development of new MEMS and NEMS technologies based on UNCD

FUTURE WORK

- **Studies of mechanical and tribological phenomena at the nanoscale in UNCD micro/nanos structures**
- **Development of microfabrication processes for and demonstration of MEMS and NEMS devices and characterization of functionalities**

FWP 57504